Review of exclusive processes at high energies: theory point of view and suggestions for future experiments

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Diffractive and electromagnetic processes at high energies
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Contents

Introduction

- Most of the high energy processes concentrated on single particle distributions (in transverse momentum or (pseudo)rapidity)
- A few body exclusive final states studied very rarely
- QCD type processes -- KMR mechanism
  - $pp \to ppH$ (Higgs boson properties)
  - $pp \to pp\chi_c$
  - $pp \to ppb\bar{b}$ (Higgs background)
  - $pp \to ppgg$
  - $pp \to pp\gamma\gamma$
  - $pp \to ppMM$ (large invariant masses of mesons)
- QED processes
  - $pp \to pp\mu^+\mu^-$ (e.m. form factors)
  - $pp \to ppW^+W^-$ (gauge boson coupling)
  - $pp \to ppm\bar{m}$ (Dirac monopoles)
  - $pp \to pp\pi^0$ (technipion)

Introduction, continued

- QCD photoproduction of vector mesons
  - $pp \to ppJ/\psi$ (search for odderon)
  - $pp \to pp\Upsilon$
  - $pp \to pp\rho(\omega, \phi)$
  - $pp \to ppZ^0$
- Production of meson pairs
  - $pp \to pp\pi^+\pi^-$ (search for glueballs)
  - $pp \to ppK^+K^-$
  - $pp \to nn\pi^+\pi^+$

mechanism of the reaction

diffractive excitation of resonances

glueballs (?)

large contribution to central diffraction cross section

low energy theorems ($gg \to \pi\pi$)

Introduction, continued

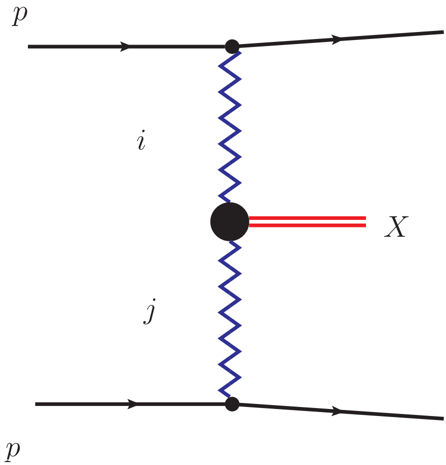
- Production of single pion
  - $pp \to pp\pi^0$
  - $pp \to pn\pi^+$

  Large cross section

  Large contribution to single diffraction cross section

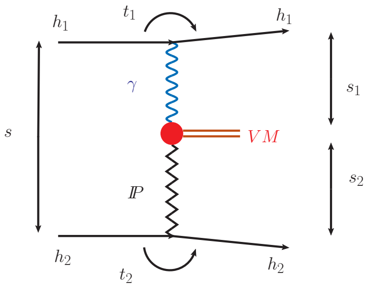
  Contribution to large rapidity production (cosmic ray interactions)
- Diffractive excitation of single resonances
- $pp \to pp\gamma$

Central exclusive production



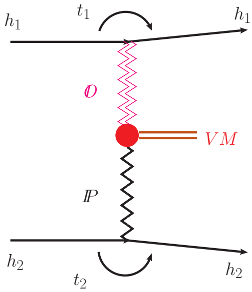
Exclusive Production of J/ψ, Υ in Hadronic Collision

Photoproduction



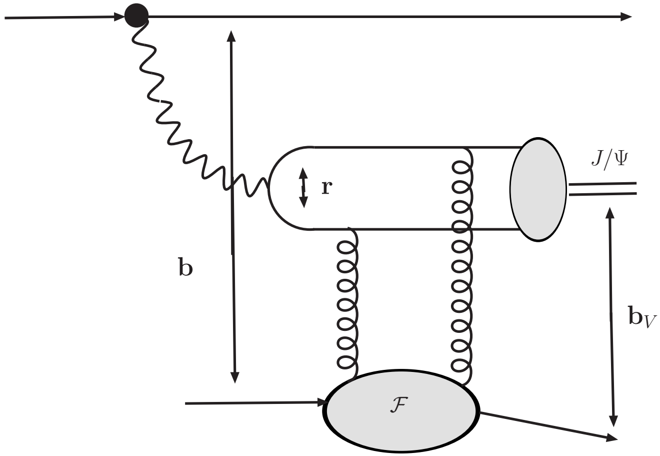
Khoze-Martin-Ryskin '02; Klein & Nystrand '04
cross section $\sim$ nanobarns

Odderon--Pomeron fusion

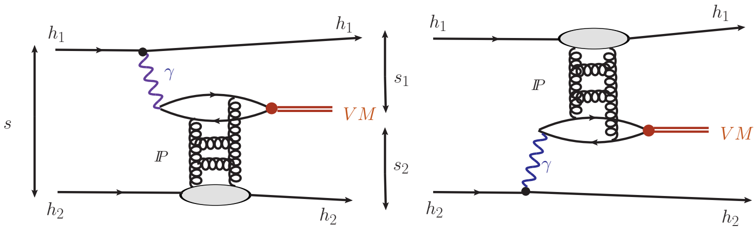


A. Schäfer, Mankiewicz & Nachtmann '91
cross section $\sim$ 0.1 nanobarns

In QCD



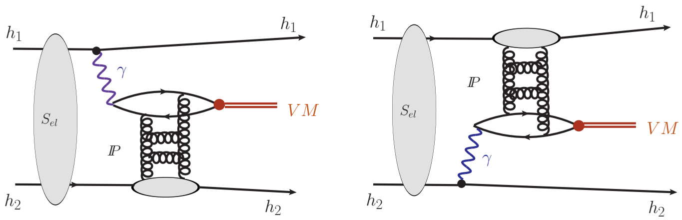
Exclusive Photoproduction in Hadronic Collisions



$$\boldsymbol{M}(\boldsymbol{p}_1,\boldsymbol{p}_2) = e_1 \frac{2}{z_1}\frac{\boldsymbol{p}_1}{t_1}\mathcal{F}_{\lambda_1'\lambda_1}(\boldsymbol{p}_1,t_1)\mathcal{M}_{\gamma^* h_2\to V h_2}(s_2,t_2,Q_1^2)$$

$$+ \; e_2 \frac{2}{z_2}\frac{\boldsymbol{p}_2}{t_2}\mathcal{F}_{\lambda_2'\lambda_2}(\boldsymbol{p}_2,t_2)\mathcal{M}_{\gamma^* h_1\to V h_1}(s_1,t_1,Q_2^2)\,.$$

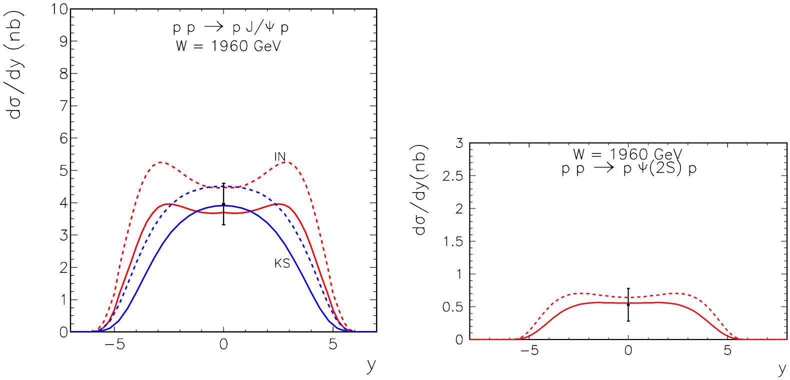
Absorption corrections



$$\boldsymbol{M}(\boldsymbol{p}_1, \boldsymbol{p}_2) \;=\; \int \frac{d^2\boldsymbol{k}}{(2\pi)^2}\, S_{el}(\boldsymbol{k})\, \boldsymbol{M}^{(0)}(\boldsymbol{p}_1 - \boldsymbol{k}, \boldsymbol{p}_2 + \boldsymbol{k})$$

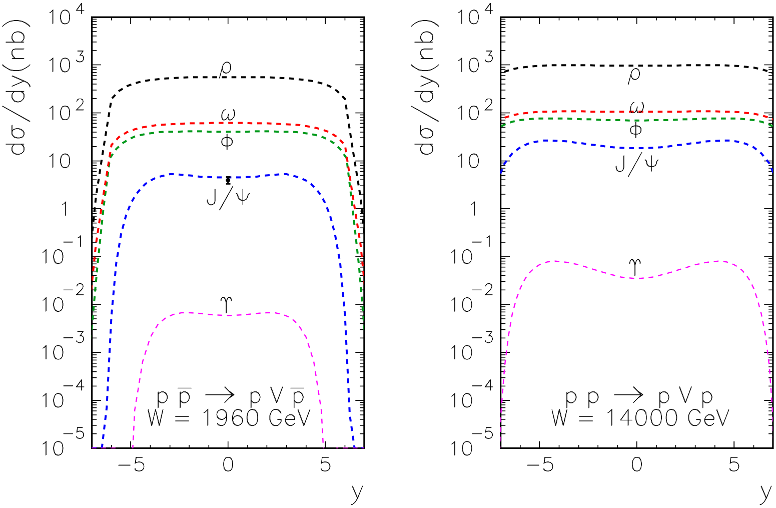
- Absorptive corrections depend on elastic $h_1 h_2$ amplitude $\longrightarrow$ taken from data.
- photon pole $\longrightarrow$ peripheral interactions $\longrightarrow$ Absorption at 20%–level.

Rapidity spectra at Tevatron

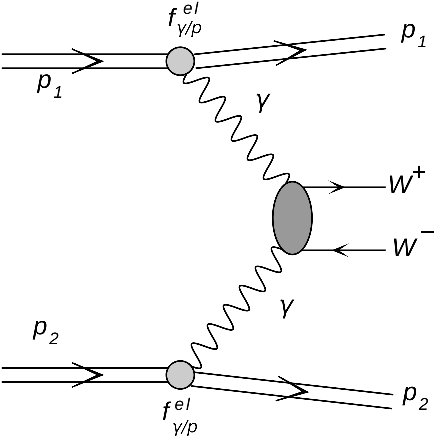


- CDF collaboration, T. Aaltonen et al. Phys. Rev. Lett. 102 (2009)
- W. Schäfer & A. Szczurek Phys. Rev. D76 (2007).
- calculations by A. Cisek, PhD thesis (2012),

Rapidity spectra at Tevatron/LHC energies



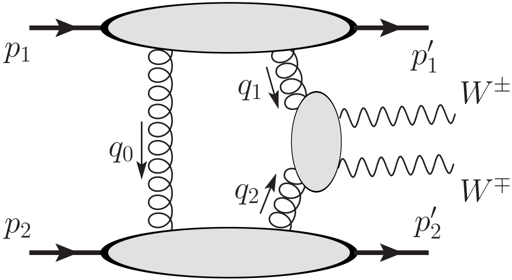
Exclusive production of W^+W^- pairs



In the moment only W^+ and W^- are measured.

In the future outgoing protons should be measured.

Diffractive exclusive production of W^+W^- pairs



Lebiedowicz, Pasechnik, Szczurek
Nucl. Phys. **B867** (2013) 61.

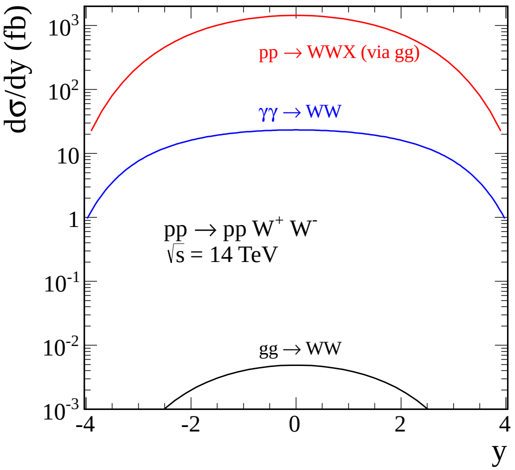
Diffractive amplitude for $pp \to ppW^+W^-$

$$\mathcal{M}_{\lambda_+\lambda_-}(s,t_1,t_2) \simeq is\frac{\pi^2}{2}\int d^2\mathbf{q}_0 V_{\lambda_+\lambda_-}(q_1,q_2,k_+,k_-) \frac{f_g(q_0,q_1;t_1)f_g(q_0,q_2;t_2)}{\mathbf{q}_0^2\,\mathbf{q}_1^2\,\mathbf{q}_2^2},$$

where $\lambda_+, \lambda_- = \pm 1, 0$ are the polarisation states of the produced $W^\pm$ bosons

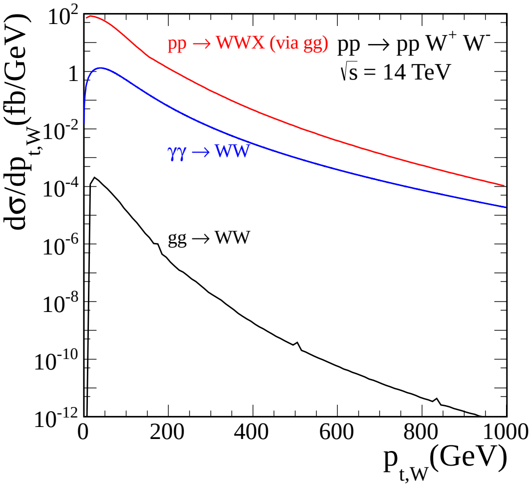
$f_g(r_1, r_2; t)$ is the off-diagonal unintegrated gluon distribution function (UGDF), which depends on the longitudinal and transverse components of both gluon momenta r_1 and r_2 emitted from the proton lines.

$pp \to ppW^+W^-$, results



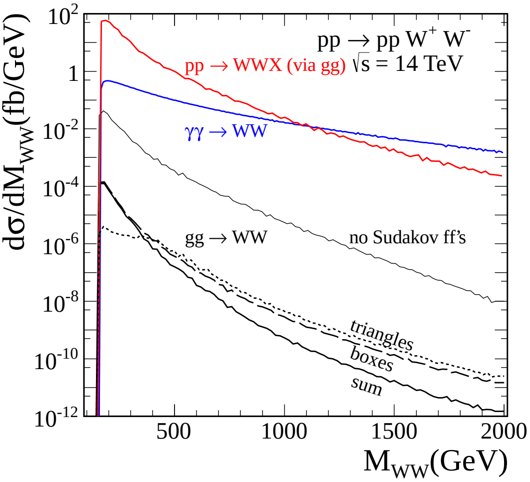
diffractive contribution very small

$pp \to ppW^+W^-$, results



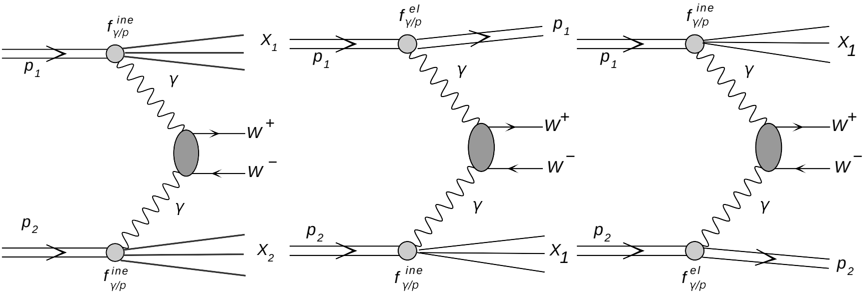
diffractive contribution very small

$pp \to ppW^+W^-$, results



diffractive contribution very small, extra canellations

Semiexclusive production of W^+W^- pairs



At present no exclusivity assured

at most a requirement of no other particles in the midrapidity region (CMS)

Inelastic photon distributions, naive approach

Some $\gamma\gamma$ induced processes ($\gamma\gamma \to H^+H^-, L^+L^-$) were discussed long time ago (Drees, Godbole, Nowakowski, Rindani). In their approach

$$f_{\gamma/p} = f_{q/p} \otimes f_{\gamma/q} \ , \tag{1}$$

which can be written mathematically as

$$x f_{\gamma/p}(x) = \sum_q \int_x^1 dx_q f_q(x_q, \mu^2) e_q^2 \left(\frac{x}{x_q}\right) f_{\gamma/q}\left(\frac{x}{x_q}, Q_1^2, Q_2^2\right) \ , \tag{2}$$

where the sum runs over all quarks and antiquarks.

Inelastic photon distributions, naive approach

The flux of photons in a quark/antiquark in their calculations was parametrized as:

$$f_\gamma(z) = \frac{\alpha_{em}}{2\pi} \frac{1 + (1 - z)^2}{2} \log\left(\frac{Q_1^2}{Q_2^2}\right) . \quad (3)$$

The choice of scales in the formulae is a bit ambigous. They have proposed the following set of scales:

$$\begin{aligned} Q_1^2 &= \max(\hat{s}/4 - m_W^2, 1^2) \\ Q_2^2 &= 1^2 \\ \mu^2 &= \hat{s}/4 . \end{aligned} \quad (4)$$

We shall try to use the approach here as a reference for more refined calculation described in the next subsection.

MRSTQ-QED parton distributions

$$\frac{\partial q_i(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{qq}(y)\; q_i(\frac{x}{y},\mu^2) + P_{qg}(y)\; g(\frac{x}{y},\mu^2)\right\}$$
$$+ \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left\{\tilde{P}_{qq}(y)\; e_i^2 q_i(\frac{x}{y},\mu^2) + P_{q\gamma}(y)\; e_i^2 \gamma(\frac{x}{y},\mu^2)\right\}$$

$$\frac{\partial g(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{gq}(y)\; \sum_j q_j(\frac{x}{y},\mu^2) + P_{gg}(y)\; g(\frac{x}{y},\mu^2)\right\}$$

$$\frac{\partial \gamma(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{\gamma q}(y)\; \sum_j e_j^2\; q_j(\frac{x}{y},\mu^2) + P_{\gamma\gamma}(y)\; \gamma(\frac{x}{y},\mu^2)\right\},$$

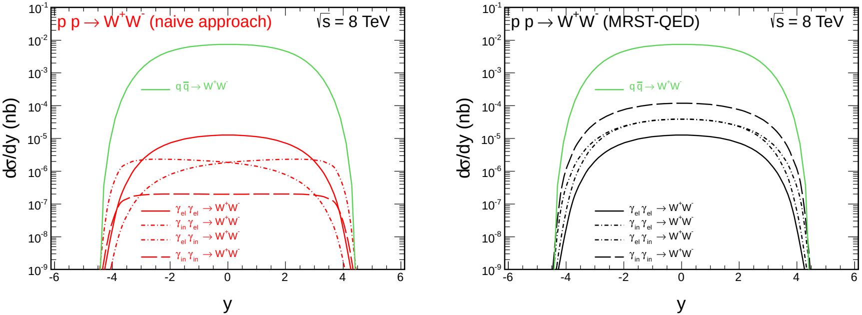
Cross sections

$$\frac{d\sigma^{\gamma_{in}\gamma_{el}}}{dy_1\,dy_2\,d^2p_t} = \frac{1}{16\pi^2\hat{s}^2} x_1\gamma_{in}(x_1,\mu^2)\; x_2\gamma_{el}(x_2,\mu^2)\; \overline{|\mathcal{M}_{\gamma\gamma\to W^+W^-}|^2}\,,$$

$$\frac{d\sigma^{\gamma_{el}\gamma_{in}}}{dy_1\,dy_2\,d^2p_t} = \frac{1}{16\pi^2\hat{s}^2} x_1\gamma_{el}(x_1,\mu^2)\; x_2\gamma_{in}(x_2,\mu^2)\; \overline{|\mathcal{M}_{\gamma\gamma\to W^+W^-}|^2}\,,$$

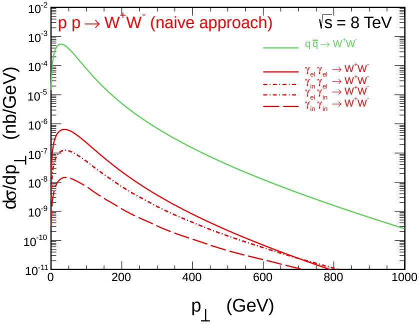
$$\frac{d\sigma^{\gamma_{el}\gamma_{el}}}{dy_1\,dy_2\,d^2p_t} = \frac{1}{16\pi^2\hat{s}^2} x_1\gamma_{el}(x_1,\mu^2)\; x_2\gamma_{el}(x_2,\mu^2)\; \overline{|\mathcal{M}_{\gamma\gamma\to W^+W^-}|^2}\,.$$

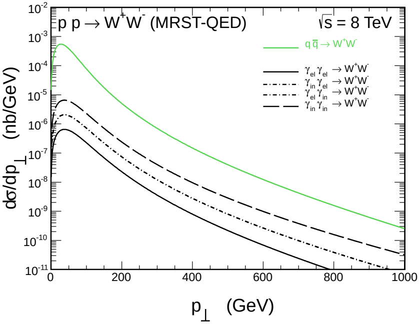
First results



large inelastic contributions in the QCD-improved approach

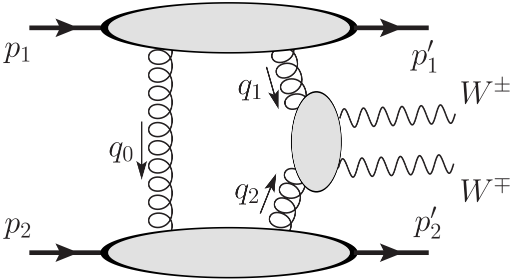
First results





large inelastic contributions in the QCD-improved approach

$pp \to pp\gamma\gamma$



Lebiedowicz, Pasechnik, Szczurek

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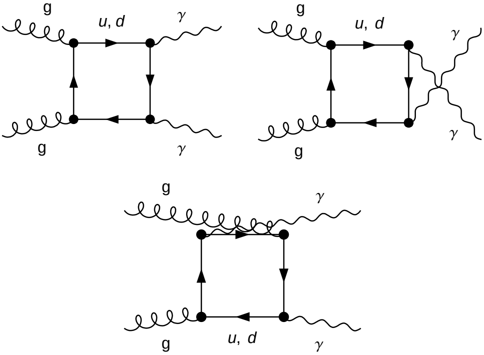
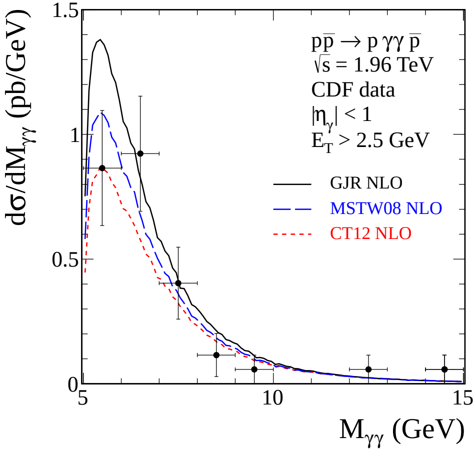
$pp \to pp\gamma\gamma$



$pp \to pp\gamma\gamma$



Lebiedowicz, Pasechnik, Szczurek

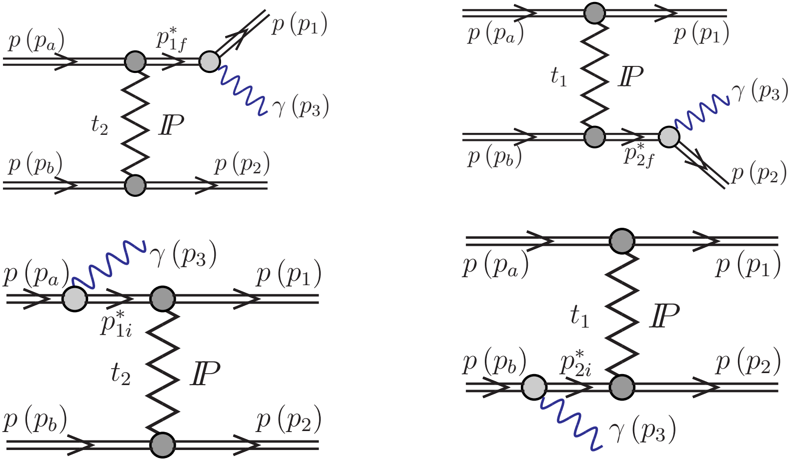
Nucl. Phys. **B867** (2013) 61.

We will consider now the $pp \to pp\gamma$ reaction.

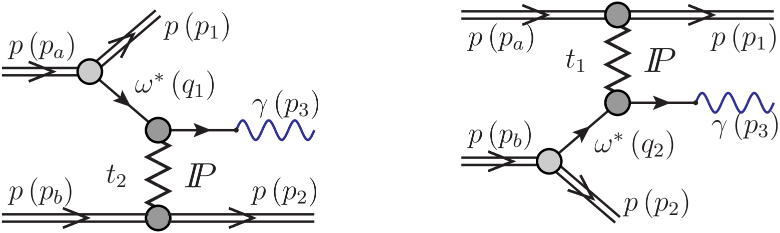
The details can be found in:

P. Lebiedowicz and A. Szczurek, ``Exclusive diffractive photon bremsstrahlung at the LHC'', Phys. Rev. **D87** (2013) 114013.

Classical bremsstrahlung



Vector meson rescattering (new)

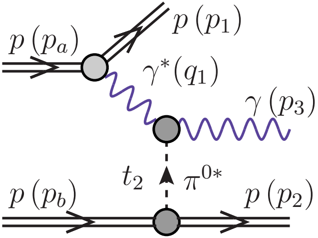


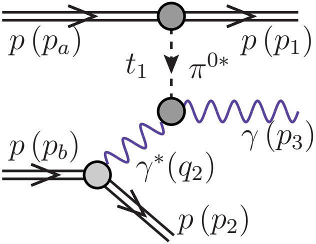
Vector meson is off-mass shell.

Similar diagrams for ρ^0 meson.

The diagrams for ω and ρ^0 interfere.

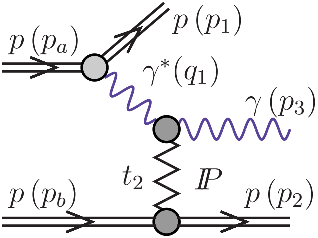
Pion cloud contribution (new)

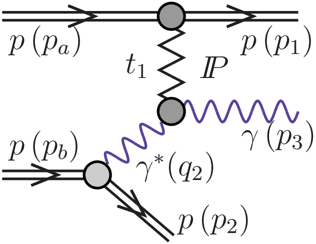




Anomalous coupling, but off-shell pion

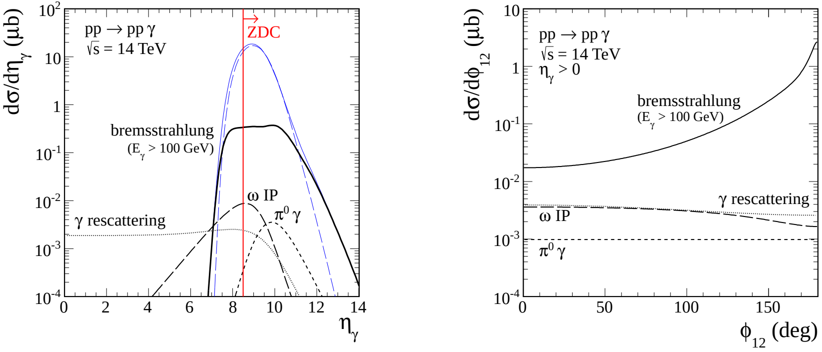
Photon rescattering (new)





photon-proton quasi-elastic scattering

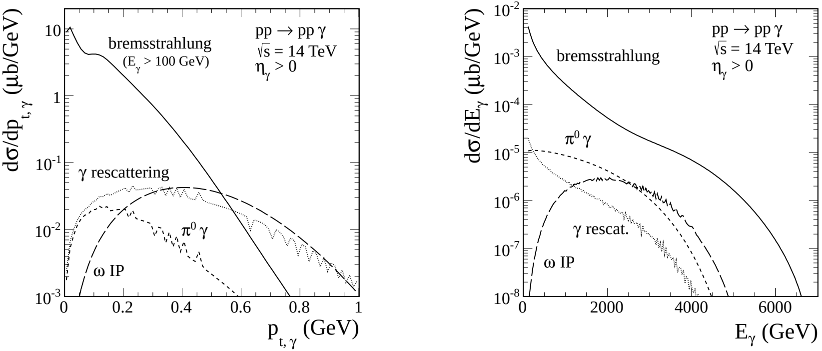
Differential distributions, page 1



Most of the mechanisms at large (pseudo)rapidities

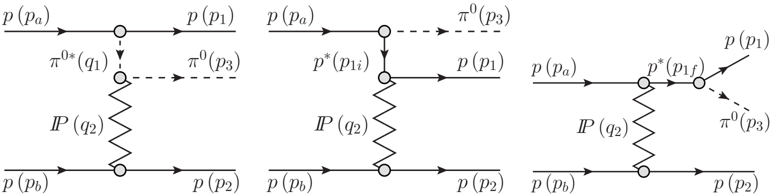
Only photon elastic rescattering at midrapidities

Differential distributions, page 2



Large energy photons, ZDC

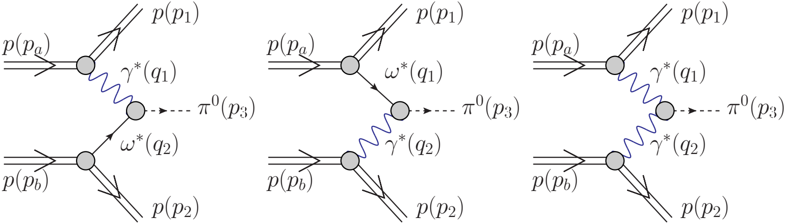
$pp \to pp\pi^0$, mechanisms



$pp \to pn\pi^+$ studied at low energies

3 diagrams: Drell-Hiida-Deck model

$pp \to pp\pi^0$, new mechanisms

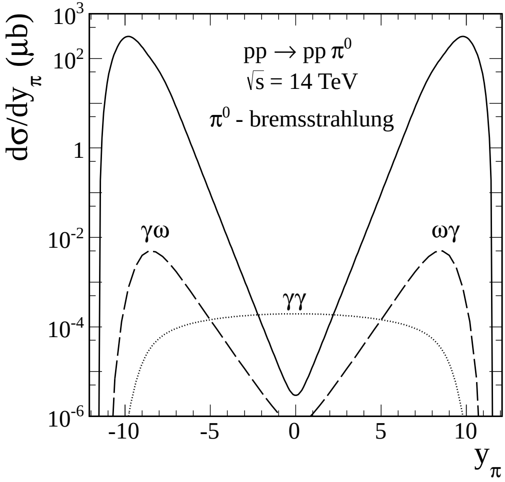


strong coupling of omega to nucleon

$\gamma^* \gamma^* \pi^0$ anomalous coupling

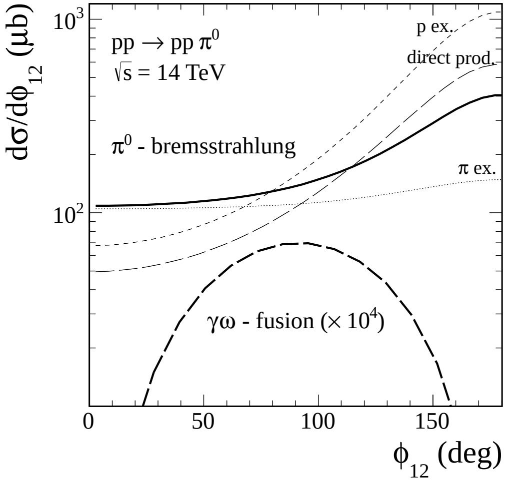
The strenght fixed from $\pi^0 \to \gamma\gamma$.

$pp \to pp\pi^0$, contributions



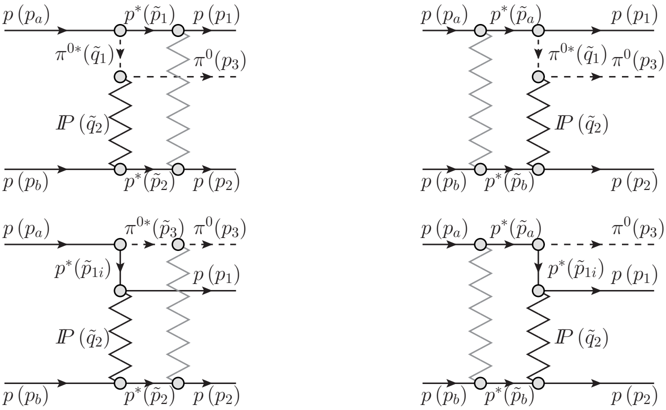
Large contribution to low-mass single diffraction

$pp \to pp\pi^0$, contributions

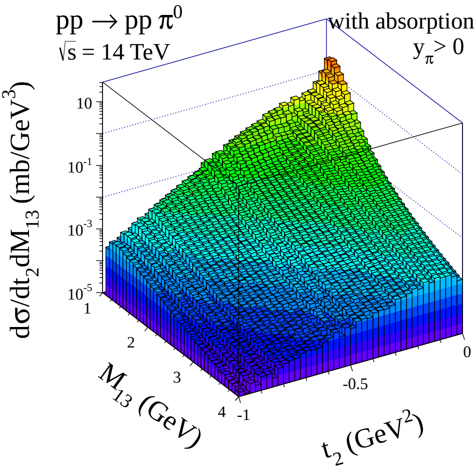


Convenient way to fix relative contribution of different diagrams

$pp \to pp\pi^0$, absorption effects



$pp \to pp\pi^0$, with absorption



mass-dependent slope

A comment on single diffractive cross section

At the LHC single diffraction (SD) and double diffraction (DD) processes constitute a large contribution to the inelastic cross section (about a half).

Low excitations are not well understood (!)

Jenkovszky, Kuprash, Orava and Salii, arXiv:1211.5841 (hep-ph)

use dual Regge model with nonlinear proton trajectories

In their model the low mass excitation is dominated by the excitation of the proton resonances:

$N^*(1440)$ with $J^P = \frac{1}{2}^+$ (not so obvious)

$N^*(1680)$ with $J^P = \frac{5}{2}^+$ (OK).

This is the region where the absorbed Drell-Hiida-Deck mechanism predicts an huge enhancement.

Our DHD mechanism contributes to the single diffraction cross section as

$$\sigma_{SD}^{DHD} = 3\, \sigma_{pp \to pp\pi^0}^{DHD} \,. \quad (5)$$

Our estimate of the DHD contribution is 1-5 mb.

Low energy excitation in single diffraction

How large is this contribution?

But elastic contribution could (in principle) be contaminated (at high energies) by other processes:

- photon bremsstrahlung
- $pp \to ppe^+e^-$
- photoproduction of Δ isobar excitation
- diffractive excitation of low-excited resonances
- DHD contribution

$$\sigma_{el}^{meas} = \sigma_{el} + \Delta\sigma \tag{6}$$

Then

$$\sigma_{in}^{meas} = \sigma_{tot} - \sigma_{el}^{meas}$$

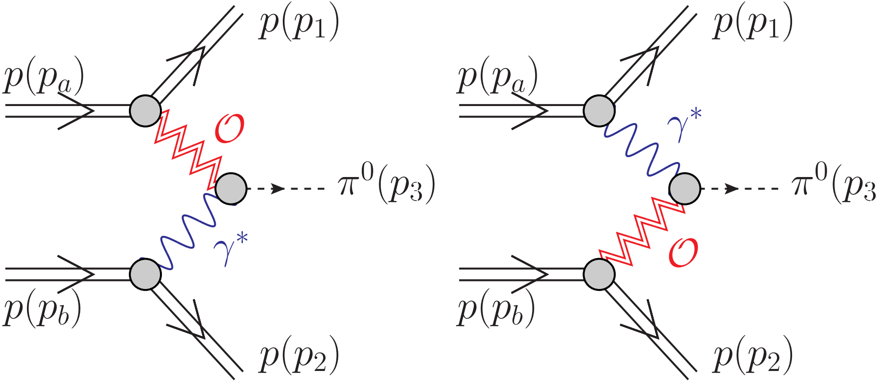
$$\sigma_{in}(M < M_0) = \sigma_{in} - \sigma_{in}^{vis}$$

This is instead

$$\sigma_{in}^{meas} - \sigma_{in}^{vis} < \sigma_{in}(M < M_0)$$

$pp \to pp\pi^0$, odderon exchanges

At midrapidity dominance of $\gamma\gamma \to \pi^0$



$pp \to pp\pi^0$, odderon exchanges

- Berger, Donnachie, Dosch, Kilian, Nachtmann, Reuter (1999) predicted cross section of 341 nb at the HERA energy.
- HERA search was negative and found only an upper limit for this process $\sigma_{\gamma p \to \pi^0 p} < 49$ nb.
- Ewerz and Nachtmann (2007) found an explanation within a nonperturbative approach using chiral symmetry and PCAC. In the chiral limit $m_\pi \to 0$ the corresponding amplitude vanishes. The amplitude is proportional to m_π^2, i.e. rather small. They have estimated that the cross section damped by a factor of 50 compared to the early estimate of BDDKNR1999.

$pp \to pp\pi^0$, odderon exchanges

The cross section for photon-odderon and odderon-photon exchanges can be estimated in the Equivalent Photon Approximation (EPA).

$$\frac{d\sigma}{dy dp_\perp^2} = z_1 f(z_1) \frac{d\sigma_{\gamma p \to \pi^0 p}}{dt_2}\left(s_{23}, t_2 \approx -p_\perp^2\right) + z_2 f(z_2) \frac{d\sigma_{\gamma p \to \pi^0 p}}{dt_1}\left(s_{13}, t_1 \approx -p_\perp^2\right) , \quad (7)$$

where $f(z)$ is an elastic photon flux in the proton.

$z_{1/2} = \frac{m_t}{\sqrt{s}} \exp(\pm y)$ with $m_t = \sqrt{m_\pi^2 + p_t^2}$.

The differential cross section $\gamma p \to \pi^0 p$ is parametrized as:

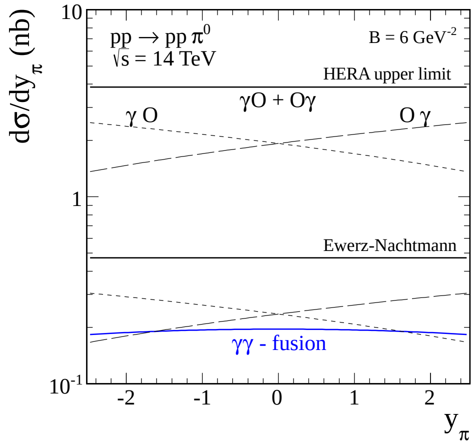
$$\frac{d\sigma}{dt} = B^2(-t) \exp(Bt) \sigma_{\gamma p \to \pi^0 p} . \quad (8)$$

The differential cross section vanishes at $t = 0$ which is due to helicity flip.

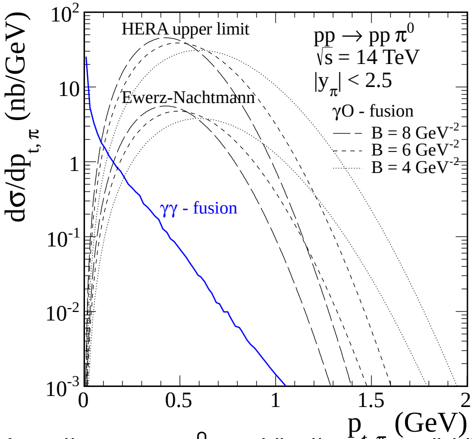
The slope parameter as for other soft processes i.e. $B \sim 4$ - 8 GeV^{-2}.

At the LHC, at midrapidities typical energies are similar as at HERA !

odderon exchanges, first results



HERA upper limit ($\sigma_{\gamma p \to \pi^0 p}$ = 49 nb) and
Ewerz-Nachtmann estimate ($\sigma_{\gamma p \to \pi^0 p}$ = 6 nb).



Any deviation from the $\gamma\gamma \to \pi^0$ contribution to p_t distribution of π^0 at midrapidity would be a potential signal of photon-odderon (odderon-photon) contributions. One can expect potential deviations from the $\gamma\gamma$ contribution at $p_t \sim 0.5$ GeV.

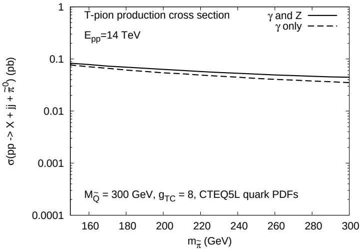
$pp \to pp\pi^0$ (technipion), introduction

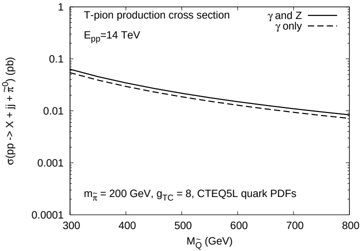
- Recently a new technicolor phenomenological model has been proposed by Pasechnik-Beylin-Kuksa-Vereshkov, arXiv:1304.2081
- The model is called Chiral-Symmetric Technicolor Model.
- In this model techniquarks (U and D) may form technipion and technisigma particles, analogues of usual pion and sigma mesons in hadronic physics.
- The techniquarks couple to usual matter via exchange of weak gauge bosons $(\gamma, Z, W^{\pm})$. So the cross sections should be smaller than in typical QCD processes where gluons are exchanged.
- The model has some parameters: m_{π^0} (technipion mass), m_Q (techniquark mass) and g_{tc} (coupling of quarks to technipions).

$pp \to pp\pi^0$ (technipion), introduction

- In inclusive processes technipions are produced in $2 \to 3$ $q_1 q_2 \to q_1, q_2 \tilde{\pi}^0$ (both quarks and antiquarks). The standard $2 \to 1$ $\gamma\gamma \to \pi^0(tc)$ approach in collinear approximation (photons being partons in the proton) gives incorrect cross section, as the main contribution comes from transverse transferred four-momenta.
- The mechanism of exclusive production of technipion is similar as the one discussed for the central exclusive production of π^0 meson. The differences are in parameters (masses and coupling constants).
- In general, there are several different combinations of exchanges: $\gamma\gamma, \gamma Z, Z\gamma, ZZ$, etc.
- At small four-momentum squared transfers the photon-photon exchanges dominate. In addition, the coupling of photons to protons is well known experimentally.

Inclusive production of technipion





calculation done by R. Pasechnik

$qq' \to qq'\pi^0(tc)$ subprocesses

rather weak dependence on masses

dominance of $\gamma\gamma$ fusion

$pp \to pp\pi^0$ (technipion)

The corresponding matrix element for the $2 \to 3$ process can be written as:

$$\mathcal{M}^{pp\to pp\pi^0}_{\lambda_a\lambda_b\to\lambda_1\lambda_2} = V^{\mu_1}(\lambda_a \to \lambda_1)\frac{(-ig_{\mu_1\nu_1})}{t_1} \mathcal{F}_{\gamma\gamma\to\pi^0}(M_Q, M_\pi)\epsilon^{\nu_1\nu_2\alpha\beta}q_{1,\alpha}q_{2,\beta} \frac{(-ig_{\mu_2\nu_2})}{t_2}V^{\mu_2}(\lambda_b \to \lambda_2)\,. \quad (9)$$

The 6-fold sum above can be easily reduced to a 4-fold sum using properties of the metric tensor.

The vertex functions can be approximated as (spin conserving only):

$$\begin{aligned} V^{\mu_1}(\lambda_a \to \lambda_1) &\approx F_1(t_1)\bar{u}(\lambda_1)i\gamma^{\mu_1}u(\lambda_a) \\ V^{\mu_2}(\lambda_b \to \lambda_2) &\approx F_1(t_2)\bar{u}(\lambda_2)i\gamma^{\mu_2}u(\lambda_b) \end{aligned} \quad (10)$$

The triangle function reads:

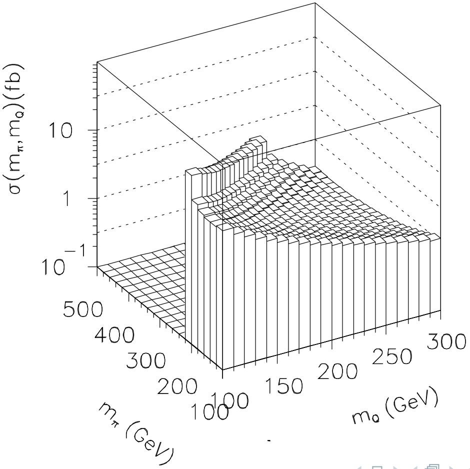
$$\mathcal{F}_{\gamma\gamma\to\pi^0}(M_Q, M_\pi) = \frac{4g_{tc}\alpha_{em}}{\pi}\frac{M_Q}{M_\pi^2} arcsin^2\left(\frac{M_\pi}{2M_Q}\right) . \tag{11}$$

The natural limitation is:

$$\frac{M_\pi}{2M_Q} < 1 . \tag{12}$$

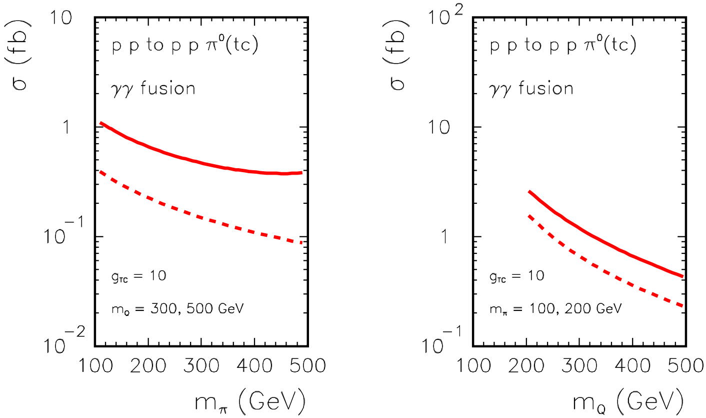
First results

Dependence of the cross section on model parameters:



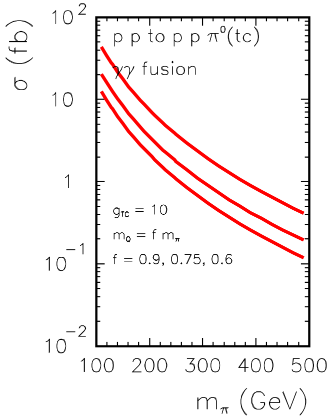
First results

Dependence of the cross section on model parameters:

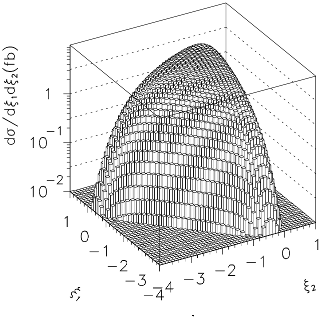


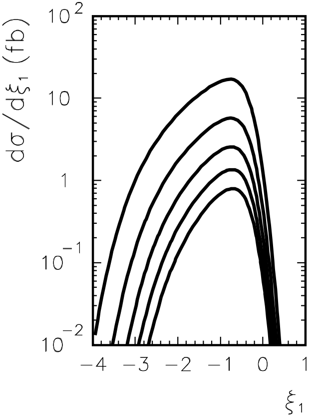
First results

Dependence of the cross section on model parameters:



some technical details

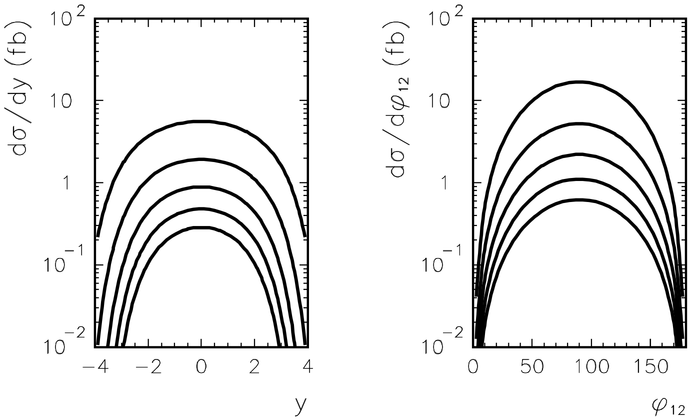




$\xi_1 = log_{10}(p_{1,t}/1GeV)$

$\xi_2 = log_{10}(p_{2,t}/1GeV)$

some differential distributions

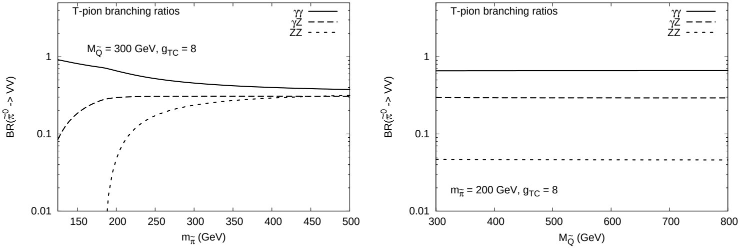


technipion centrally produced

Select in ϕ_{12} arround 90° to reduce background?

Observation channel?

Branching fractions for $\pi(tc)$ decay



$\gamma\gamma$ channel the best option

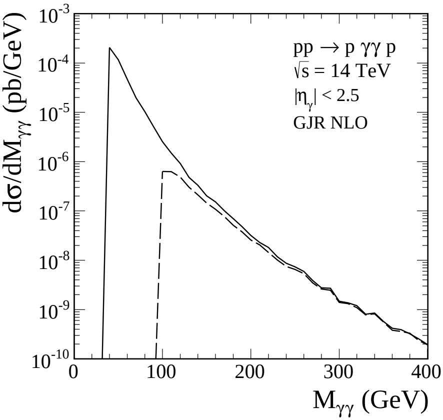
However, big background for inclusive reactions.

In exclusive reaction:

impose lower cut on transverse momentum of photons to get rid of soft backgrounds

KMR pQCD mechanism is the biggest background at large transverse momenta for exclusive process.

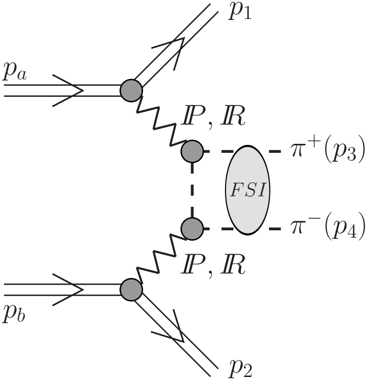
Two-photon background (KMR mechanism)



calculation done by P. Lebiedowicz

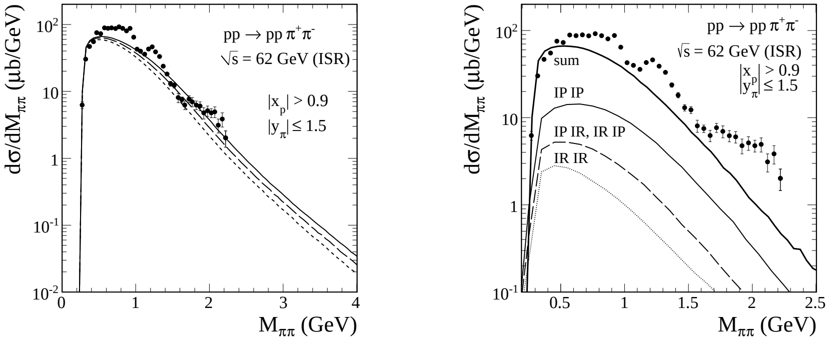
Cross section drops quickly with $\gamma\gamma$ invariant mass.

$pp \to pp\pi^+\pi^-$



Double-pomeron exchanges searched for in 1970's

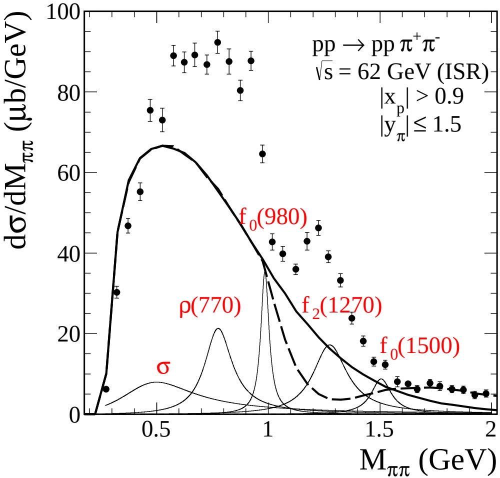
$pp \to \pi^+\pi^-$ at ISR



Large contribution of non-DPE even at $\sqrt{s}$ = 62 GeV.

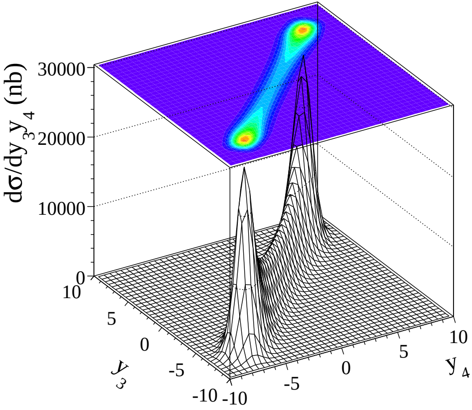
P. Lebiedowicz and A. Szczurek, Phys. Rev. **D81** (2010) 036003.

Resonance contributions



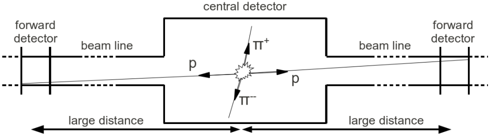
Waiting for consistent inclusion of continuum and resonances

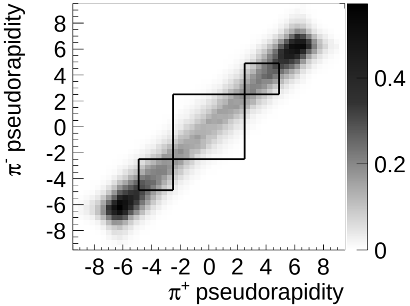
$y(\pi^+) \times y(\pi^-)$ correlations



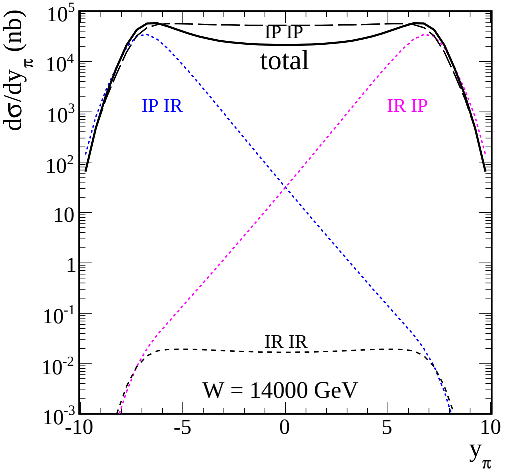
We predict funny camel-like shape

A measurement with ALFA@ATLAS



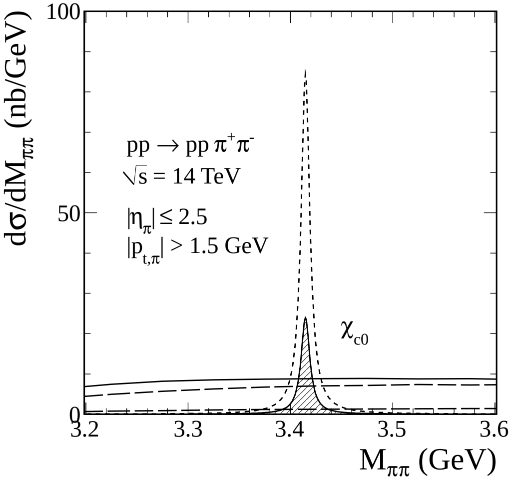


R. Staszewski, P. Lebiedowicz, M. Trzebiński, J. Chwastowski and A. Szczurek, Acta Phys. Polon. **B42** (2011) 181.



Reggeon exchanges still important, even at LHC

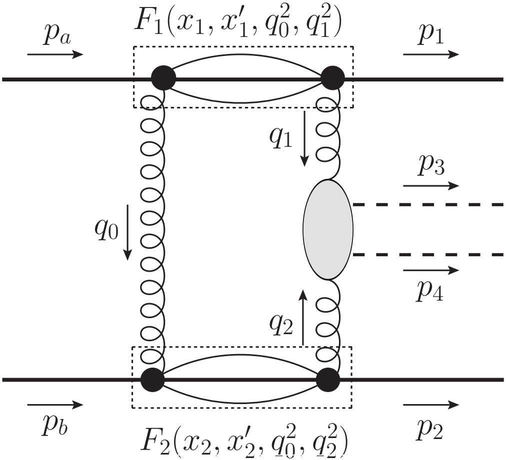
$\chi_c(0) \to \pi^+\pi^-$



Difficult in $\chi_c(J^+) \to J/\Psi\gamma$ channel

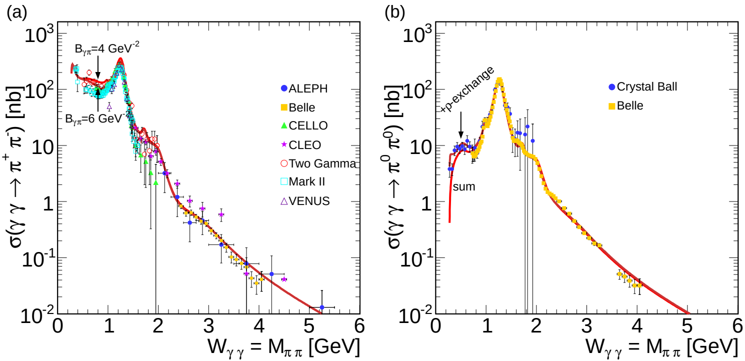
$gg \rightarrow \pi\pi$ nonperturbative coupling

competitive mechanism:



UGDF in nonperturbative region

$AA \to AA\pi\pi$



Good description of elementary $\gamma\gamma \to \pi\pi$ reactions

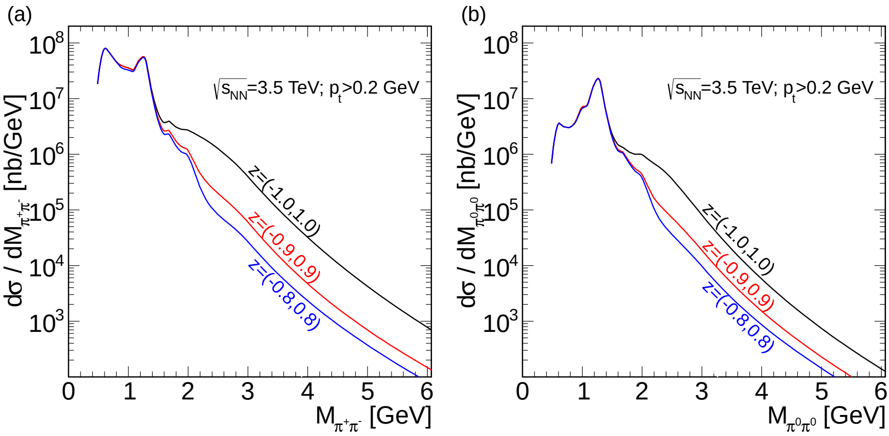
Klusek, Szczurek, Phys. Rev. **C87** (2013) 054908.

$AA \to AA\pi\pi$, total cross section

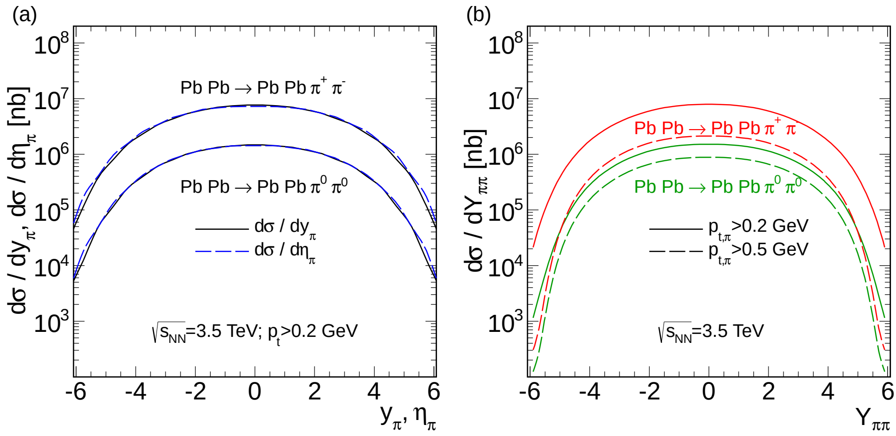
Table: Cross sections for different lower cuts on pion transverse momenta at $\sqrt{s_{NN}}$ = 3.5 TeV.

$p_{t,min}$ (GeV)	$\pi^+\pi^-$ (mb)	$\pi^0\pi^0$ (mb)
0.2	46.7	8.7
0.5	12.1	5.1
1.0	0.08	0.05

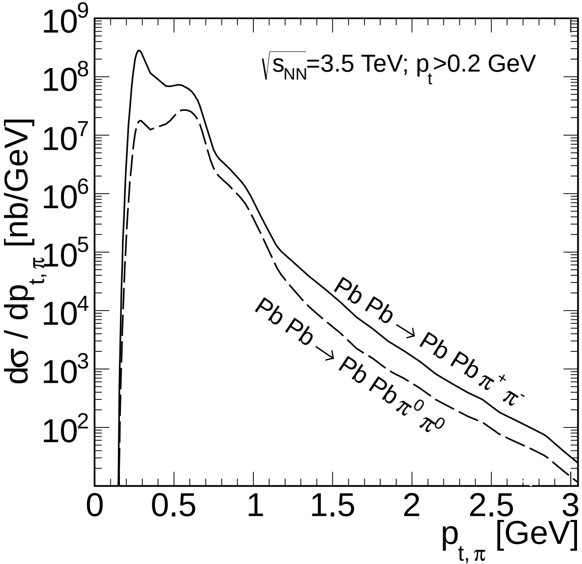
$AA \to AA\pi\pi$, differential distributions



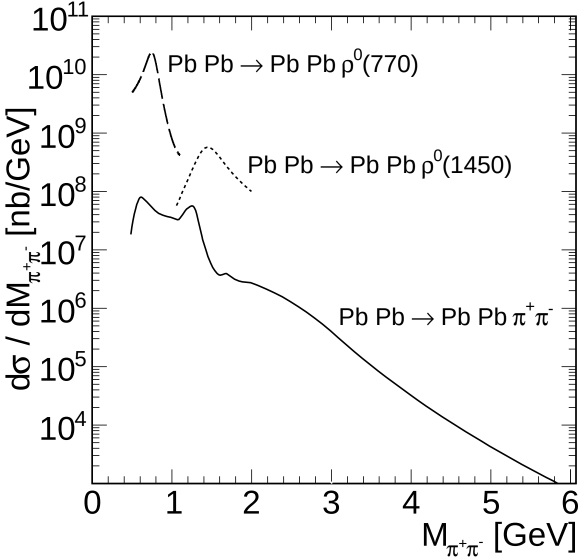
$AA \to AA\pi\pi$, differential distributions



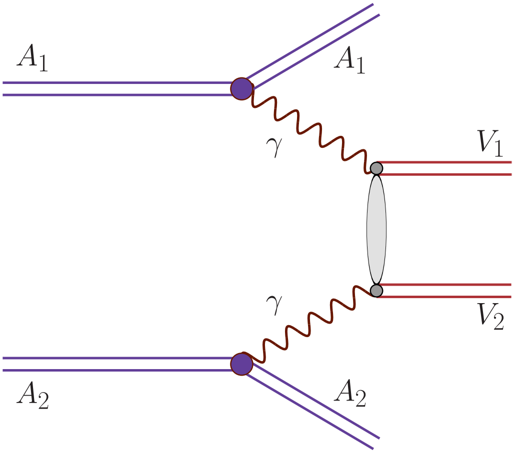
$AA \rightarrow AA\pi\pi$, differential distributions



$AA \to AA\pi\pi$, differential distributions

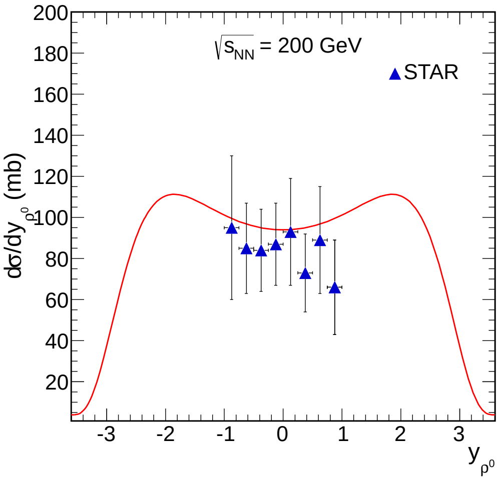


$AA \to AA\rho^0\rho^0$



Klusek-Schäfer-Szczurek, Phys. Lett. **B674** (2009) 92.

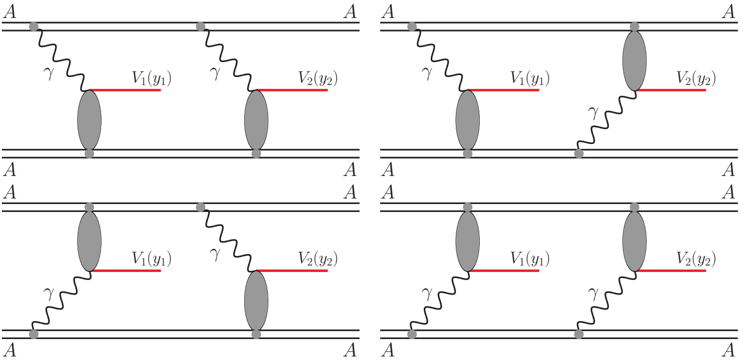
$AA \to AA\rho^0$



huge cross section (!)

$AA \to AA\rho^0\rho^0$

double-scattering mechanism



Klusek-Gawenda and Szczurek, a paper ready to submit.

$AA \to AA\rho^0\rho^0$, double scattering

$$\sigma_{AA\to AAV_1V_2}(\sqrt{s_{NN}}) = C \int P_{V_1}(b, \sqrt{s_{NN}}) P_{V_2}(b, \sqrt{s_{NN}}) d^2b \,, \qquad (13)$$

where the probability of single meson production is

$$P_V(b, \sqrt{s_{NN}}) = \frac{d\sigma_{AA\to AAV}(b; \sqrt{s_{NN}})}{2\pi b db} \,. \qquad (14)$$

The simple formula (13) can be generalized to calculate two-dimensional distributions in rapidities of both vector mesons

$$\frac{d\sigma_{AA\to AAV_1V_2}}{dy_1 dy_2} = C \int S_{el}^2(b) \left(\frac{dP_1^{\gamma}(b, y_1; \sqrt{s_{NN}})}{dy_1} + \frac{dP_1^{\gamma}(b, y_1; \sqrt{s_{NN}})}{dy_1} \right) \times \left(\frac{dP_2^{\gamma}(b, y_2; \sqrt{s_{NN}})}{dy_2} + \frac{dP_2^{\gamma}(b, y_2; \sqrt{s_{NN}})}{dy_2} \right) d^2b$$

$AA \to AA\rho^0\rho^0$, double scattering

$$S_{el}^2(b) = \exp\left(-\sigma_{NN}^{tot} T_{A_1A_2}(b)\right) \approx \partial\left(b - (R_1 + R_2)\right) \; . \tag{16}$$

It may be interpreted as a survival probability for nuclei not to undergo break up of nuclei.

dP_1 and dP_2 are probability densities to produce one vector meson V_1 at rapidity y_1 and second vector meson V_2 at rapidity y_2, respectively, for fixed impact parameter b. Then the more differential probability can be written as:

$$\frac{dP_V(b, \sqrt{s_{NN}})}{dy} = \frac{d\sigma_{AA \to AAV}(b; \sqrt{s_{NN}})}{2\pi b db dy} \; . \tag{17}$$

Smearing the ρ^0 masses

In a more refined approximation (b) one has to include in addition a smearing of the ρ^0 mass. Then the cross section can be written as

$$\frac{d\sigma_{AA\to AA\rho_0^*\rho_0^*}}{dm_1 dm_2 dy_1 dy_2} = f(m_1) f(m_2) \frac{d\sigma_{AA\to AA\rho_0^*\rho_0^*}}{dy_1 dy_2}(y_1 y_2; m_1, m_2) \,, \tag{18}$$

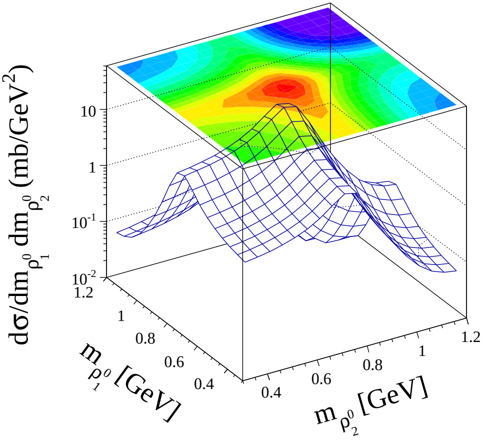
where m_1 and m_2 are running masses of ρ^0 mesons and $f_1(m_1)$ and $f_2(m_2)$ are respective distributions. The last term is the cross section for running masses m_1 and m_2. The spectral shapes are calculated as:

$$f(m) = |\mathcal{A}|^2 / \int |\mathcal{A}|^2 dm \,, \tag{19}$$

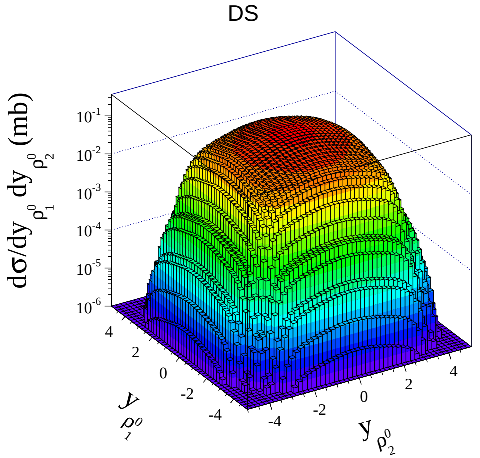
where the amplitude is parametrized as:

$$\mathcal{A} = \mathcal{A}_{BW} \frac{\sqrt{m m_\rho \Gamma(m)}}{m^2 - m_\rho^2 + i m_\rho \Gamma(m)} + \mathcal{A}_{\pi\pi} \,. \tag{20}$$

$AA \to AA\rho^0\rho^0$, mass smearing

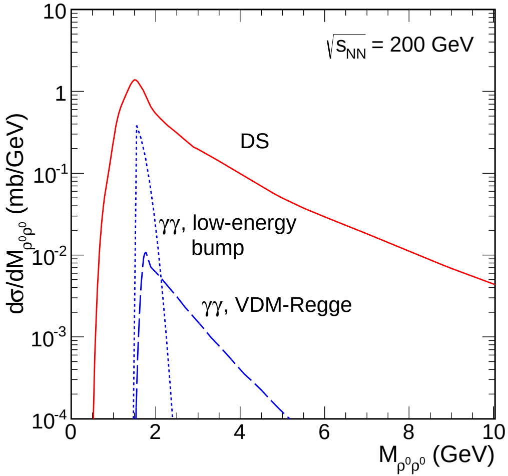


$AA \to AA\rho^0\rho^0$, first results



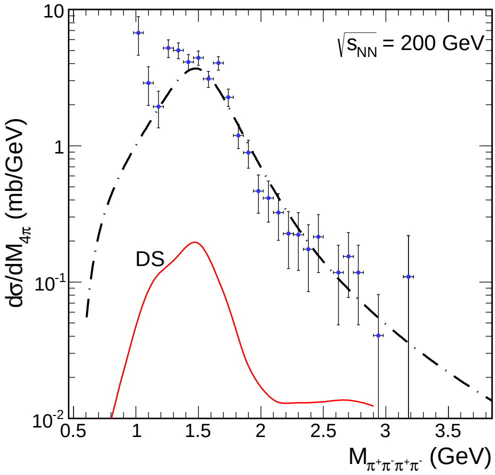
rather flat distribution compared to $\gamma\gamma$ contribution

$AA \longrightarrow AA\rho^0\rho^0$, first results



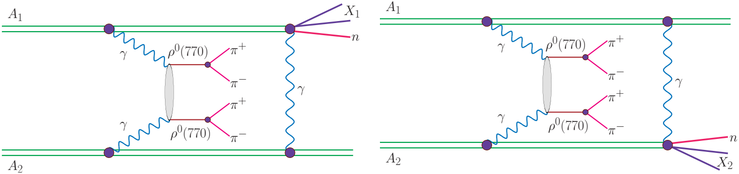
double scattering contribution much bigger than photon-photon

$AA \longrightarrow AA\rho^0\rho^0$, first results



Other mechanism at RHIC! How to identify double scattering?

Neutrons measured in ZDC



Neutrons can be measured by Zero Degree Calorimeters

They are a "good trigger" for the exclusive reactions

Neutron emission

Cross section for production of ``something'' with a given number of neutrons in each ZDC

is an interesting (measureable) quantity,

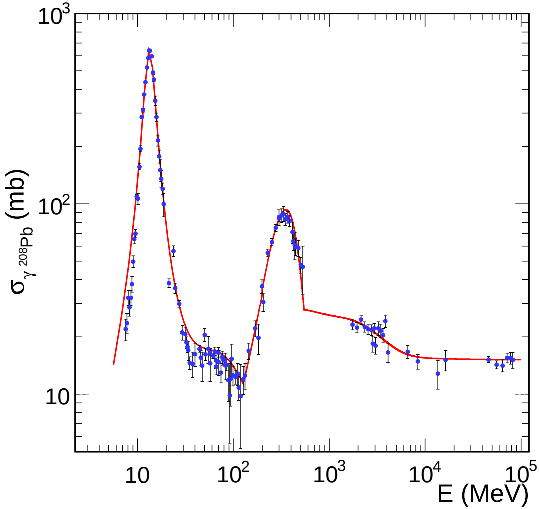
$\sigma_{AA \to AAX}(n_1, n_2)$

X = 0 (Coulomb excitation), ρ^0, $\mu^+\mu^-$, etc

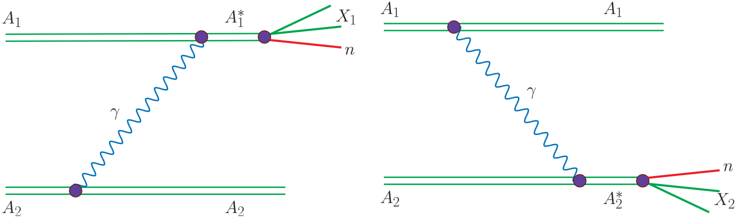
For each exclusive process one can do the following table (topological cross section):

	0 neutrons	1 neutron	2 neutrons	3 neutrons	....
0 neutrons					....
1 neutron					....
2 neutrons					....
3 neutrons					....
....					....

photon-^{208}Pb cross section



Electromagnetic dissociation



Huge damping of heavy-ion fluxes at LHC !

Electromagnetic dissociation - a bit of formalism

In the single photon-exchange approximation the cross section for dissociation of second and first nucleus:

$$\begin{aligned}
\sigma^{(1)} &= \int d^2b \int d\omega_1 \frac{d^3n(b,\omega_1)}{d\omega_1 d^2b} S(b) \sigma_{\gamma A_2 \to A_2^*}(\omega_1) \, . \\
\sigma^{(2)} &= \int d^2b \int d\omega_2 \frac{d^3n(b,\omega_2)}{d\omega_2 d^2b} S(b) \sigma_{\gamma A_2 \to A_2^*}(\omega_2) \, ,
\end{aligned} \tag{21}$$

Of course: $\sigma^{(1)} = \sigma^{(2)}$.

Above $S(b)$ can be interpreted as a survival probability of the nuclei not to desintegrate.

Electromagnetic dissociation - a bit of formalism

$$S(b) \approx \partial\left(|\mathbf{b}| - \mathbf{R_1} - \mathbf{R_2}\right) \ . \qquad (22)$$

$\frac{d^3 n(b,\omega)}{d\omega d^b}$ is a flux of equivalent photons.
In some approximation:

$$\frac{dN}{d\omega_{1/2} d^2 b} = \frac{Z^2 \alpha_{em} X^2}{\pi^2 \omega_{1/2} b^2} K_1^2(X) \qquad (23)$$

Notice Z^2 enhancement compared to protons.

Electromagnetic dissociation - a bit of formalism

The total cross section for dissocition of either A_1 or A_2 can be written as:

$$\sigma_{diss} = \sigma^{(1)} + \sigma^{(2)} \ . \qquad (24)$$

A differential distribution (integrand of total cross section) may be interesting

$$\frac{d\sigma^{(1)}}{d^2b d\omega_1} = \frac{d^3n(b,\omega_1)}{d\omega_1 d^2b} \sigma_{\gamma A_2 \to A_2^*}(\omega_1) \ ,$$

$$\frac{d\sigma^{(2)}}{d^2b d\omega_2} = \frac{d^3n(b,\omega_1)}{d\omega_2 d^2b} \sigma_{\gamma A_1 \to A_1^*}(\omega_2) \ ,$$

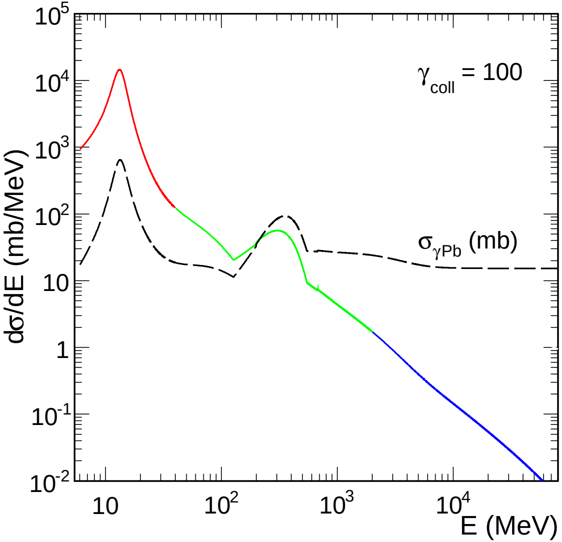
Electromagnetic dissociation

Cross section in barns

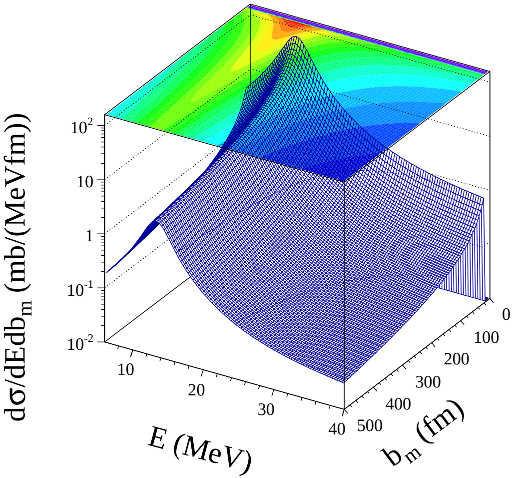
	(6-40) MeV	(40-2000) MeV	(2-80) GeV
$\gamma_{coll} = 100$			
Our results	80.16	25.6	5.6
$\gamma_{coll} = 3100$			
Our results	133.8	54.6	18.7

Could we measure the electromagnetic dissociation at LHC ?

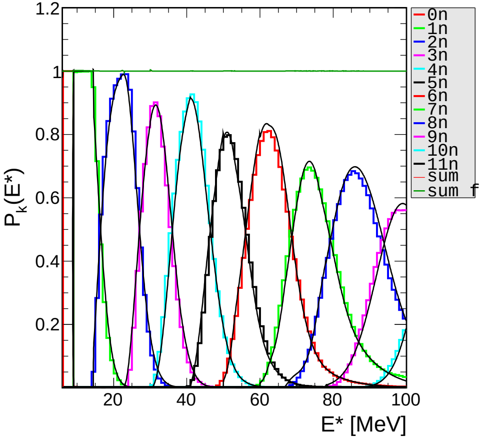
Electromagnetic excitation



Electromagnetic excitation



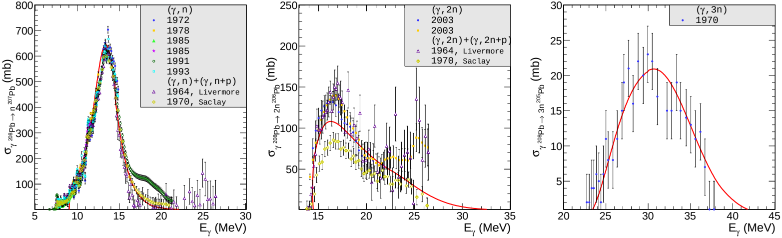
Neutron production from excited nucleus



Hauser-Feshbach theory (M. Ciemała)

The approach assumes equilibrated excited nucleus (!)

Cross section for single neutron photoproduction



Surprisingly good agreement!

Model assumes equilibrium.

Does it mean the nucleus goes to equilibrium after photon absorption and before neutron emission?

Electromagnetic dissociation with forward/backward neutrons

first nucleus in ground state, second nucleus excited

$$\sigma_{0*}^{(i)} = 2\pi \int dbbS(b) \int_{E_{min}}^{E_{max}} d\omega_1 \frac{dN}{d\omega_1 d^2b} \sigma_{\gamma A_2 \to A_2^*}(\omega_1) P_{A_2}^{i}(E_2^*) \; ,$$

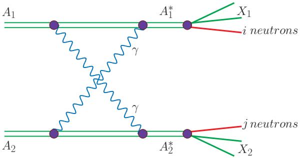
$E_2^* = \omega_1$?

first nucleus excited, second nucleus in the ground state

$$\sigma_{*0}^{(j)} = 2\pi \int dbbS(b) \int_{E_{min}}^{E_{max}} d\omega_2 \frac{dN}{d\omega_2 d^2b} \sigma_{\gamma A_1 \to A_1^*}(\omega_2) P_{A_1}^{j}(E_1^*) \; ,$$

$E_1^* = \omega_2$?

Mutual excitation



Second-order effects lead to mutual excitations. Then first nucleus emits i neutrons and second nucles j neutrons

$$\sigma_{**}^{(i,j)} = 2\pi \int dbbS(b)$$

$$\left(\int_{E_{min}}^{E_{max}} d\omega_1 \frac{dN}{d\omega_1 d^2 b} \sigma_{\gamma A_2 \to A_2^*}(\omega_1) P^i_{A_2}(E_2^*)\right) \left(\int_{E_{min}}^{E_{max}} d\omega_2 \frac{dN}{d\omega_2 d^2 b} \sigma_{\gamma A_1 \to A_1^*}(\omega_2) P^j_{A_1}(E_1^*)\right)$$

cm

Both excitations independent (no correlations).

Conclusions

- Extremely large span of rapidities at the LHC
- Different processes could be measured in unexplored region of energies.
- Testing photoproduction at much larger energies than at HERA.
- Searches for odderon possible in exclusive vector and π^0 meson production.
- A search for technipions produced via photon-photon fusion.
- Searches for glueballs possible in exclusive production of $\pi^+\pi^-$ or K^+K^- pairs.
- Many exclusive channels contribute to single diffration ($pp \to pp\pi^0$) or central diffraction ($pp \to pp\pi\pi$) cross section.

Conclusions

- Many interesting nonperturbative effects:
  - low energy phenomena at high energies.
  - testing the nature of the pomeron (e.g. its spin structure)
- $\gamma\gamma$ production of pionic pairs in exclusive nuclear collisions gives a background to $\rho^0(770)$ and its higher excitations.
- Large double scattering contribution to exclusive $\rho^0\rho^0$ production in nuclear peripheral collisions. Open question: how to identify different components?.

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